CCD imaging system for precision beam steering in laser communications

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Abstract. A CCD imaging system has been developed for precision laser beam pointing. The system contains a high frame rate CCD camera operated in windowing mode under command of an embedded processor. A laser pointing and tracking update rate of 2 KHz has been achieved.

Subject terms: CCD cameras, laser pointing, laser communications.

1 introduction

Precision beam pointing in laser communications typically requires acquisition of an incoming beacon laser, high bandwidth tracking in the presence of satellite jitter, and point-ahead of an outgoing transmit laser. Traditionally, these functions have been implemented by configuring a number of detectors and fine beam steeling elements that result in a complex massive beam pointing system. In order to develop a compact laser communication package for satellite applications, it is desirable to build a precision beam pointing system with small complexity [1]. This can be achieved by using a CCD array with sufficiently large format and high frame rate such that all the functions of acquisition, tracking, and point-ahead can be performed with only one detector and one fine beam steering element [1,2]. Recent] y, we have customized a CCD camera with a format of 128x128 which can be operated under command of a DSP board. With this camera, we have completed a demonstration of closed-loop beam steering with point-ahead at an update rate of 2 KHz. This paper describes the CCD-based imaging and pointing system.

2 Pointing technique

Figure 1 shows the concept of laser pointing based on a CCD array as the only detector. First, an incoming beacon laser beam is searched for by using a gimbal to steer the telescope and the CCD camera attached behind it. Once the beacon image is found on the CCD array, it is maintained on the array by determining the centroid of the beacon image and closing a coarse tracking loop around the telescope gimbal. The low frequency disturbances of the platform are compensated for by the gimbal control loop. As a result, the position of the beacon image will be confined in a small window on the array corresponding to the rms high frequency uncompensated jitter. An outgoing transmit laser beam is then reflected off a 2-axis fine steering mirror attached to the telescope. A small portion of the transmit beam is imaged on the CCD array, and the rest exits through the telescope optics towards the beacon laser with a point-ahead angle. The separation between the beacon and transmit beam images on the CCD array is found by determining their centroids, and is a direct measure of the point-ahead angle. A fine tracking control loop is closed around the steering mirror to stabilize the point-ahead angle with high accuracy. Figure 2 shows a block diagram of the pointing control loop, where the coarse gimbal control loop acts only on the beacon line of sight while the mirror control loop stabilizes the transmit/receive point-ahead angle.

The above technique does not require fine stabilization of the beacon line of sight. Furthermore, the point-ahead angle compensation is accommodated on the same CCD array and by the same steering mirror. As a result, this technique does not require additional detectors and beam steering elements as in conventional pointing techniques, and results in a less complex pointing system. A CCD array with a format of> 100x100 and a field of view of 1 mrad, that can be read out and processed at 2 KHz in windowing mode, is appropriate for satellite laser pointing and communications. The laser image sizes will be about 2x2 pixels, with processing window sizes of about 6x6 pixels. Given the attitude knowledge accuracy, platform disturbance spectra[3,4], and relative velocities of typical Earth orbiting spacecraft, the above CCD array allows beacon search times of under ten seconds, pointing accuracy of few micro radians, and point-ahead angles of few hundreds of microradians.

3 CCD hardware

The CCD camera is based on the CA-D1 128x128 camera manufactured by Dalsa, Inc. In its normal mode of operation as supplied by the manufacturer, the camera runs in full frame readout mode with a frame rate of 840 Hz at a maximum horizontal readout rate of 16 MHz. For tracking applications, processing of pixel data reduces the frame rate to only a few hundred Hz. To obtain a high tracking frame rate, we have modified the timing electronics of the camera such that it can be interfaced to and commanded by a DSP board, and operated in windowing mode. Through its program, the DSP issues commands to the CCD camera for single vertical shifts in image and/or storage planes. The command and data interface between the DSP and CCD camera, and the resulting windowing operation of the camera are described below.

3.1 Command and data interface

The DSP commands single CCD vertical shifts by writing to a dedicated memory address on its address and data bus. The write memory cycle signal is sent to a custom programmable array logic (PAL) device inside the CCD camera which generates vertical CCD clock signals for a single vertical shift, and sends an acknowledgment signal back to the DSP bus. The single vertical shift can happen either in only the CCD storage. plane or in both the image and storage planes, depending on a flag signal that is set by the DSP and supplied to the PAL. Upon each vertical shift, horizontal pixel transfer out of the CCD shift register is automatically initiated unless a new vertical shift command is issued by the DSP. A FIFO circuit is used for the asynchronous transfer of CCD pixel data into the DSP board. The pixel data is stored in the FIFO circuit to be read later by the DSP through its data bus. During the DSP write cycle, the actual data from the DSP is the number of leading pixel data to be bypassed and not stored in the FIFO.

3.2 Windowing operation

Operating the CCD camera in windowing mode should be performed in a way that does not allow accumulation of residual charge in the CCD horizontal shift register, and the resulting image degradation and loss of centroid accuracy. The windowing operation is performed as follows. For each CCD frame, the full image is first transferee completely from image plane to storage plane by issuing a sequence of 128 vertical shift commands. "J'hen, fast vertical shifts are carried out in only the storage plane without horizontal pixel transfer in order to skip unnecessary rows above the window of interest. A single row immediately above the window is transferred out in order to clear the CCD shift register from accumulated charge due to skipped rows. For each CCD row passing through the window, the leading unnecessary pixels are transferred out of CCD shift register but not stored in the FIFO. The pixel data of the window are stored in the FIFO at 16 MHz. The DSP board reads the FIFO at 5 MHz and processes the window pixel data in real time without storing them in its memory. If centroid processing of current row's window pixel data is completed before all the current row pixels are transferred out of the CCD shift register, the next vertical shift command from the processor will not be executed until those pixels arc transferred out. This is necessary to ensure that residual charge in CCD shift register from one row will not corrupt pixel data from the next row.

Using the above CCD windowing hardware, we have demonstrated closed loop beam steering with point-ahead at a tracking update rate of 2 KHz, The pointing system can also be easily used as an imaging system by specifying a single 128x128 window in the DSP program. Figure 3 shows such a CCD image containing the two laser spots, Furthermore, the pointing system can be readily upgraded to incorporate a 256x256 or 512x512 CCD array with otherwise minimal changes in hardware. Because of the windowing scheme, the frame rate will not drop significantly and will still be more than 1.5 KHz for a 256x256 CCD array, allowing pointing and imaging with a larger field of view.

4 Conclusions

By operating a 128x1 28 CCD array in windowing mode under command of a DSP board, we have obtained a tracking update rate of 2 KHz in a fine tracking loop that uses a steering mirror to stabilize the point-ahead angle between a beacon and a transmit laser beam, without the need to accurately stabilize the beacon line of sight. This technique will potentially result in development of laser pointing hardware with reduced complexity for satellite laser communication applications.

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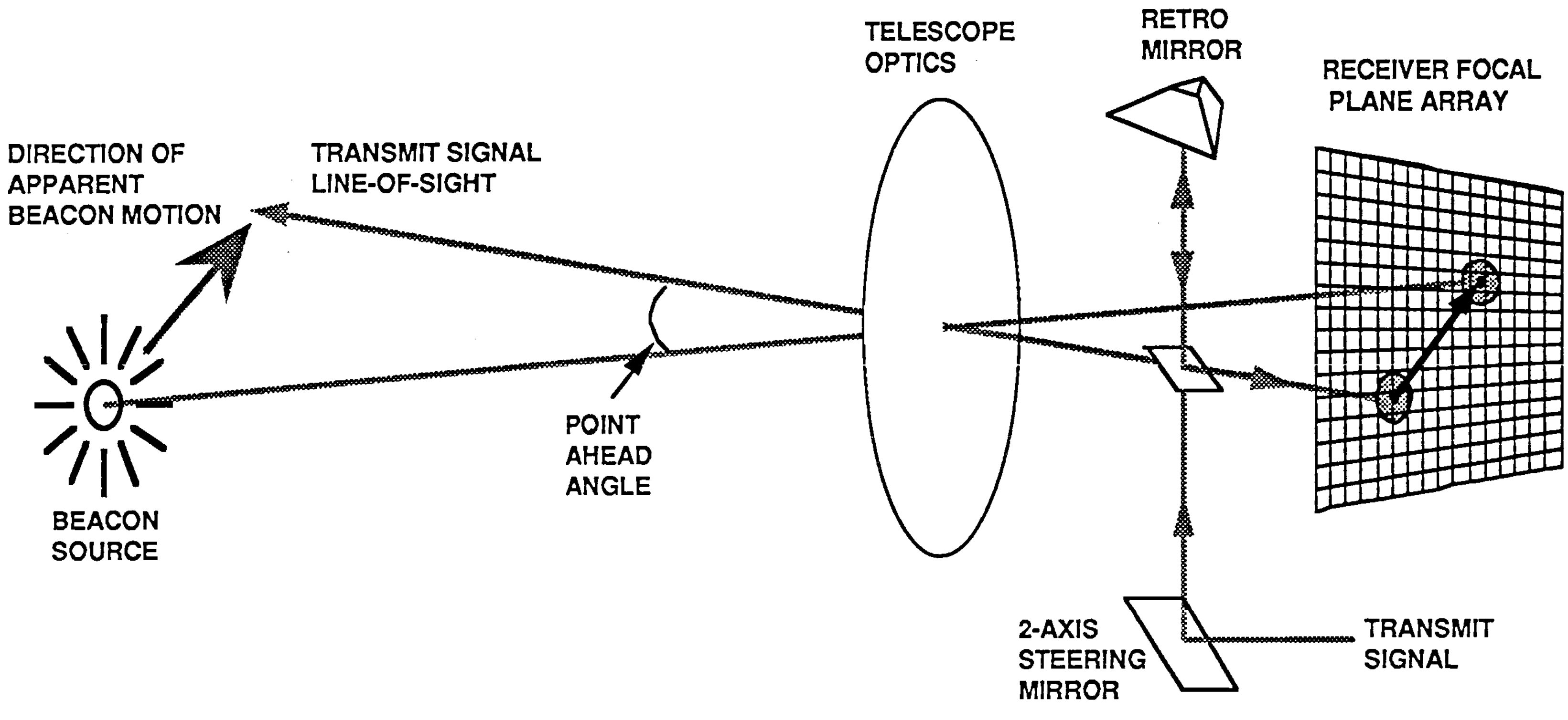


Figure 1 Pointing scheme

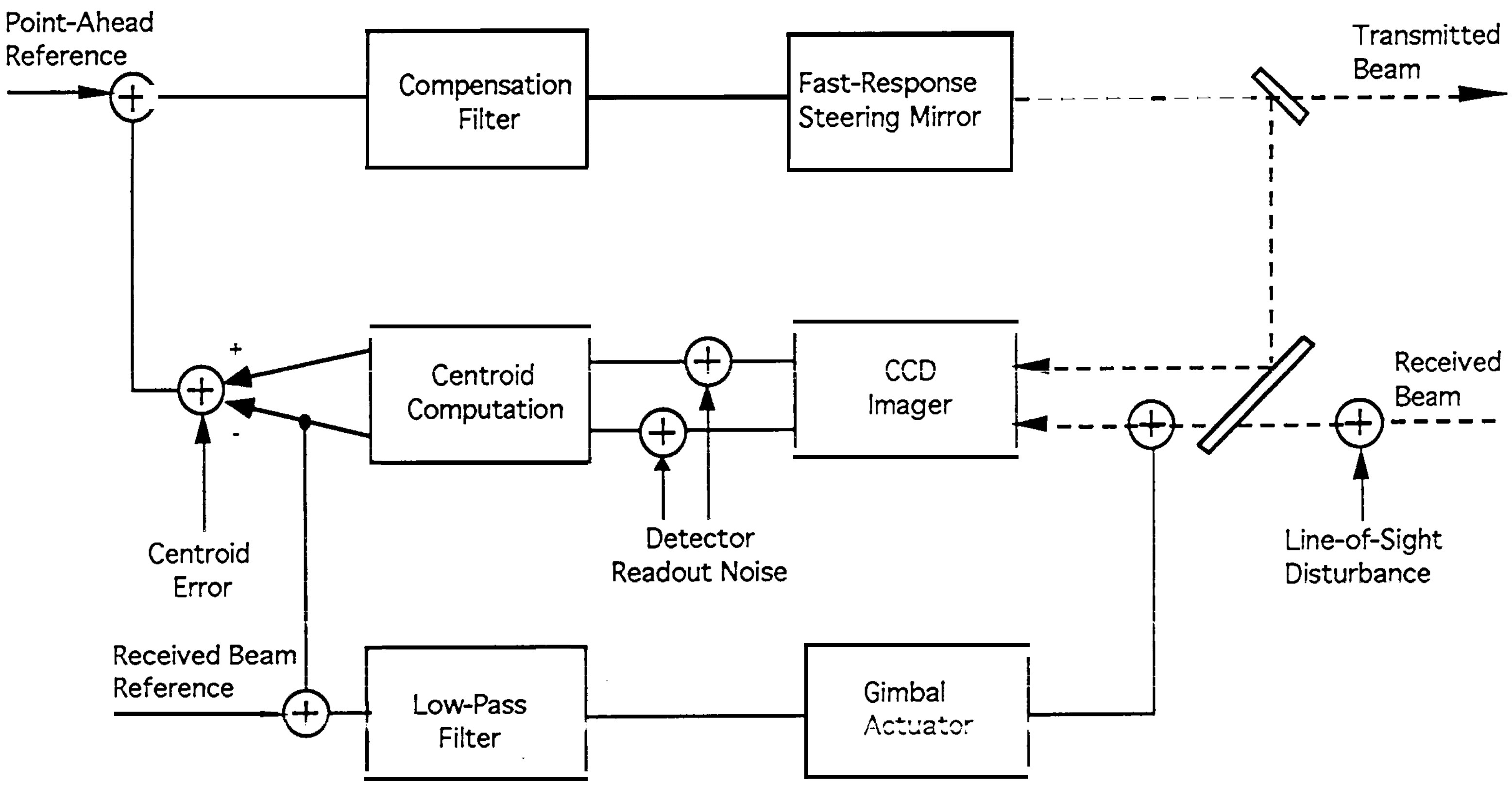
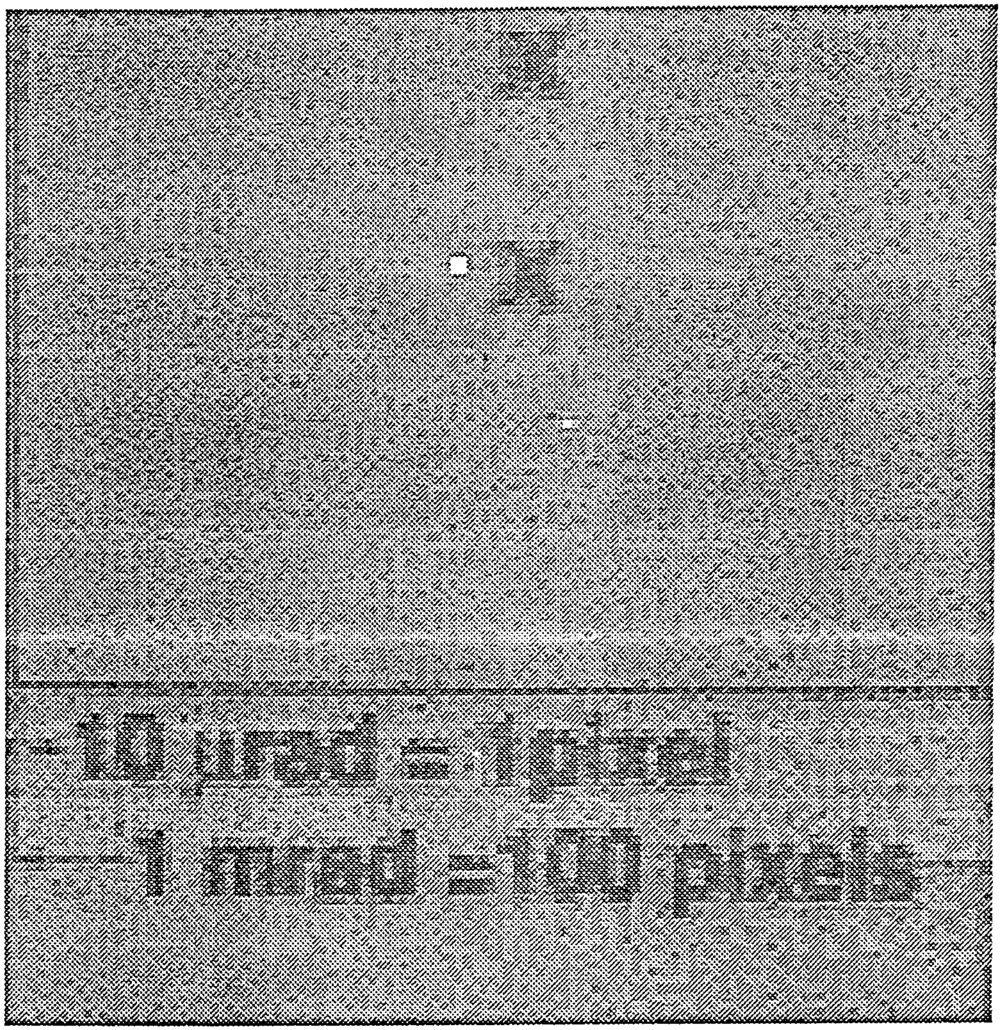


Figure 2 Pointing control loop

Figure 3 CCD image (128x128)


10 urad = 1 pixel
1 mrad = 100 pixels